All Motion is Relative

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Vigyan Prasar

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The World Year of Physics

The Year 2005 has been designated the "World Year of Physics" by United Nations coinciding with the centenary of the enunciation of the Theory of Relativity. Albert Einstein's seminal paper entitled "On the Electrodynamics of Moving Bodies" appeared in *Annalen der Physik* in 1905. It was a breakthrough in the history of physics centuries after Isaac Newton enunciated the laws of motion and the law of universal gravitation. Theory of Relativity–special and general–has stood the test of time for a century now, and remains one of the greatest creations of human mind that helps us understand nature in the proper perspective.

The year 2005 not only marks the centenary of the Theory of Relativity, it also marks the centenary of the Golden Decade 1895 – 1905 in which momentous discoveries in physics were made, say, for example; X-rays in 1895, Radioactivity and Zeeman Effect in 1896, the Electron in 1897, Quantum Theory in 1900 and explanation of Photoelectronic Effect and Relativity in 1905. This period also witnessed the first trans-Atlantic telegraphic radio transmission and the existence of ionosphere. Surely, Theory of Relativity is a feather in the cap of discoveries made in this decade. Individually, each discovery had enormous significance, while collectively; they heralded what we today call "Modern Physics".

The practitioners of classical physics of that period claimed that all the great discoveries had already been made and the physics would be reduced merely to measurements of greater and greater accuracy. Surely, a few discoveries did lie in the next decimal place as revealed by the discovery of argon during very accurate measurements of the constituents of air. The enormous advances around 1895 brought into question or directly contradicted theories that appeared to have been strongly supported by experimental evidence. For example, the experiments of Hertz demonstrated, beyond doubt, the fundamental nature of Maxwell's electromagnetic

theory of light. Yet, by an irony of fate, these very experiments of Hertz brought to light the new phenomenon of the photoelectric effect, which played an important role in establishing the Quantum Theory.

There is no story more fascinating, enlightening, and inspiring than an account of the events and the people who made the fundamental discoveries possible during the decade 1895 – 1905. A peep in the lives of these makers of modern science, their approach and methods, dedication and sacrifice with an ardent desire to share their knowledge with others, provides an insight into the process and methodology of science. The discovery of Radioactivity by Becquerel is a beautiful example of the scientific method at work – that goes on to show that discovery is more of a process rather than an event.

Mentioned above are only a few pages from the history of science and technology that has shaped our present day lives. This story is inspiring and enlightening, not only for scientists but also for the common man. Recognition did not come instantaneously to them. They had their own share of misfortune and failures. But a trait common to all of them was a positive approach and a scientific outlook in whatever they did.

Celebrating the Year of Physics is, therefore, celebrating 100 years of the golden decade, and offers a great opportunity to communicate the basic scientific aspects of these discoveries and how they have shaped our lives, promote the method of science, and spread a scientific outlook among the people. Numerous programmes, conferences, and festivals would be organized the world over to celebrate the "World Year of Physics". Vigyan Prasar (VP) has planned activities built around the work and lives of the makers of modern physics in collaboration with NCSTC and other agencies. Also planned is a variety of software – publications, films, radio and TV programmes, CD - ROMs, and slide shows; and resource material for training programmes of resource persons.

New Delhi
January 27, 2005

Dr. V.B. Kamble
Director
Vigyan Prasar

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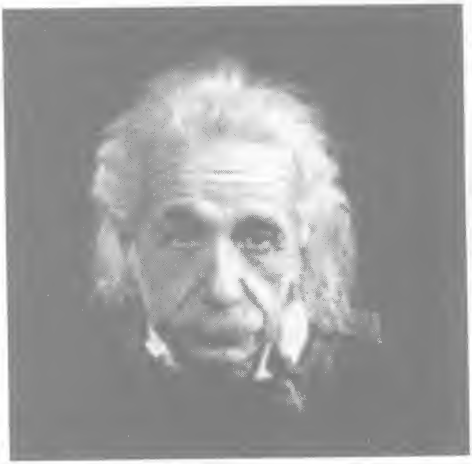
Albert Einstein

Albert Einstein (14 March 1879 – 18 April 1955) was the only son of Hermann and Pauline Einstein. He grew up in Munich, where his father and his uncle ran a small electrochemical plant. Einstein was a slow child and disliked the school. He grew interested in science early by the mysterious compass his father gave him when he was about four;



Albert Einstien

by the algebra he learned from his uncle; and by the books he read, mostly popular scientific works of the day. A geometry text which he read at the age of twelve made a particularly strong impression.When his family moved to Milan after a business failure, leaving the fifteen-year-old boy behind in Munich to continue his studies, Einstein quit the school he disliked. He spent most of a year enjoying life in Italy. Persuaded that he would have to acquire a profession to support himself, he finished the Gymnasium in Aarau, Switzerland, and then

studied physics and mathematics at the Eidgenössische Technische Hochschule (the Polytechnic) in Zurich.

After graduation, Einstein was unable to obtain a regular position for two years and did occasional tutoring and substitute teaching. Later, he was appointed an examiner in the Swiss Patent Office at Berne. Indeed, the seven years Einstein spent at this job, with only evenings and Sundays free for his own scientific work, were years in which he laid the foundations of large parts of twentieth-century physics. They were also the happiest years of his life. He liked the fact that his job was quite separate from his thoughts about physics, so that he could pursue these freely and independently. He often recommended such an arrangement to others later on In 1903 Einstein married Mileva Maric, a Serbian girl who had been a fellow student in Zurich. Their two sons were born in Switzerland.

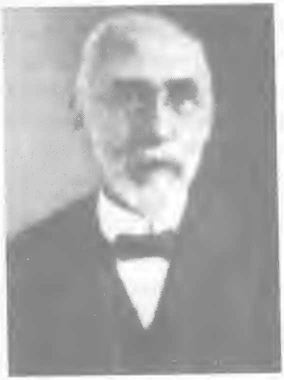
Einstein received his doctorate in 1905 from the University of Zurich for a dissertation entitled, "Eine neue Bestimmung der Moleküldimensionen" ("A New Determination of Molecular Dimensions"). This work was closely related to his studies of Brownian motion. It took a few years before he received academic recognition for his work, and then he had a wide choice of positions. His first appointment, in 1909, was as associate professor of physics at the University of Zurich. This was followed quickly by professorships at the German University in Prague, in 1911, and at the Polytechnic in Zurich, in 1912. Then, in the spring of 1914, Einstein moved to Berlin as a member of the Prussian Academy of Sciences and director of the Kaiser Wilhelm Institute for Physics. He was free to lecture at the university or not as he chose. He found the scientific atmosphere in Berlin very stimulating, and he greatly enjoyed having colleagues like Max Planck, Walther Nernst, and, later, Erwin Schrödinger and Max von Laue. During World War I, Einstein's scientific work reached a culmination in the general theory of relativity.

Mileva, Einstein and their two sons spent the war years in Switzerland. There were divorced soon after the end of the war. Einstein then married his cousin Elsa, a widow with two daughters. Einstein's health suffered, too. One of his few consolations was his continued correspondence and occasional visits with his friends in the Netherlands--Paul Ehrenfest and H. A. Lorentz, especially the latter.

Einstein became suddenly famous to the world at large when the deviation of light passing near the sun, as predicted by his general theory of relativity, was observed during the solar eclipse of 1919. His name and the term *relativity* became household words. The publicity that ensued changed the pattern of Einstein's life.

In 1933 Einstein was considering an arrangement that would have allowed him to divide his time between Berlin and the new Institute for Advanced Study at Princeton. But when Hitler came to power in Germany, he promptly resigned his position at the Prussian Academy and joined Princeton. Princeton became his home for the remaining twenty-two years of his life. He became an American citizen in 1940.

During the 1930's Einstein was convinced that the menace to civilization embodied in Hitler's regime could be put down only by force. In 1939, at the request of Leo Szilard, Edward Teller, and Eugene Wigner, he wrote a letter to President Franklin D. Roosevelt pointing out the dangerous military potentialities offered by nuclear fission and warning him of the possibility that Germany might be developing nuclear weapons. This letter helped to initiate the American efforts that eventually produced the nuclear reactor and the fission bomb. It is interesting to note that Einstein neither participated in nor knew anything about these efforts.



Hendrik Antoon Lorentz

Einstein received a variety of honours in his lifetime – from the 1921 Nobel Prize in physics to an offer (which he did not accept) of the presidency of Israel in 1952.

"Equations are for ever"

One of Einstein's last acts was his signing of a plea, initiated by Bertrand Russell, for the renunciation of nuclear weapons and the abolition of war. He was drafting a speech on the current tensions between Israel and Egypt when he suffered an attack due to an aortic aneurysm. He died a few days later. *But despite his concern with world problems and his willingness to do whatever he could to alleviate them, his ultimate loyalty was to his science.* As he said once with a sigh to an assistant during a discussion of political activities: "Yes, time has to be divided this way, between politics and our equations. But our equations are much more important to me, because politics is for the present, but an equation like that is something for eternity."

Einstein's early interests lay in statistical mechanics and intermolecular forces. However, his predominant concern throughout the career was the search for a unified foundation for all of physics. The disparity between the discrete particles of matter and the continuously distributed electromagnetic field came out most clearly

in Lorentz' (1853-1928) electron theory, where matter and field were sharply separated for the first time. This theory strongly influenced Einstein. The problems generated by the incompatibility between mechanics and electromagnetic theory at several crucial points claimed his attention. His strengths with these problems led to his most important early work – the special theory of relativity and the theory of quanta in 1905.

Albert Abraham Michelson

The discovery of X-rays, radioactivity, the electron and the quantum theory brought about a sea change in our ideas and understanding of phenomena at the atomic level. The world of Physics was, however, changing in far reaching ways - with ramifications for our understanding of the very shape of time, space and the universe. This part of the revolution was brought about Albert Einstein, a brilliant and creative theorist and the only thinker ever to be ranked in the same class as Newton. To understand this part of the revolution, we shall need to go back to James Clerk Maxwell (1831-1879) and his ideas about light.

Ether – Unbroken from star to star

Maxwell had introduced a revolutionary set of equations that predicted the existence of electromagnetic fields and established that magnetism, electricity and light were a part of the same spectrum: the electromagnetic spectrum. Light, he maintained, was a wave, not a particle, and he thought that it travelled through an invisible medium he called "the ether", which filled all space. But physicists began to see a problem, not with Maxwell's electromagnetic field equations, but with his ideas about the ether.

Maxwell wasn't the first to come up with this idea that some invisible medium called the ether must fill the vastness of space, extending "unbroken from star to star". It dated back to the time of ancient Greeks. "There can be no doubt," Once he said in a lecture in 1873, "that the interplanetary and interstellar spaces are not empty but are occupied by a material substance or body, which is certainly the largest, and probably the most uniform, body of which we have any knowledge". The idea of the ether seemed necessary because, if light was a wave, it seemed obvious that it had to be a wave travelling in some medium. But accepting what "seems

obvious" is not the way to do good science; if the ether existed, it should be possible to find some proof of its existence.

The most famous "failed" experiment in Physics

Albert Michelson (1852-1931), an American Physicist, had an idea. If the ether that filled the universe were stationary, then the planet Earth would meet resistance as it moved through the ether. This would create a current, a sort of "wind", in the ether. It followed that a light beam moving with the current ought to be carried along by it, whereas a light beam travelling against the current should be slowed. While studying with Hermann von Helmholtz (1821-1894) in Germany, in 1881 Michelson built an instrument called an interferometer, which could split a beam of light, running the two halves perpendicular to each other, and then rejoin the split beam in a way that made it possible to measure differences in the speeds with great precision.

Michelson was puzzled by the results of his experiments. They showed no differences in light velocity for the two halves of the light beam. He concluded, "The result of the hypothesis of a stationary ether is not as expected and the necessary conclusion follows that the hypothesis is erroneous".

Could it be that But may be his results were wrong? He tried his experiment again and again, each time trying to correct for any possible error. Finally, in 1887, joined by Edward Morley, Michelson tried a test in Cleveland, Ohio. Using improved equipment, and taking every imaginable precaution against inaccuracy, this time surely they would succeed in detecting the ether. **But the experiment failed again.** What were the salient features of this momentous experiment.

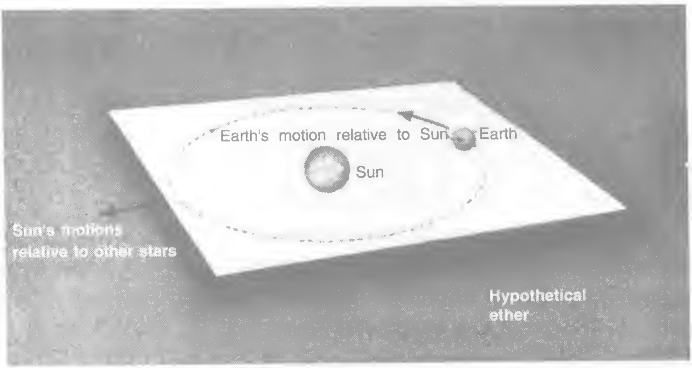


Fig 1 : Motions of the Earth through a hypothetical ether

The Experiment

If there is an ether pervading space, we move through it with at least the 3×10^4 m/sec speed of the earth's orbital motion about the Sun; if the Sun is also in motion, our speed through the ether is even greater (Figure 1). From the point of view of an observer on the earth, the ether is moving past the earth. To detect this motion,

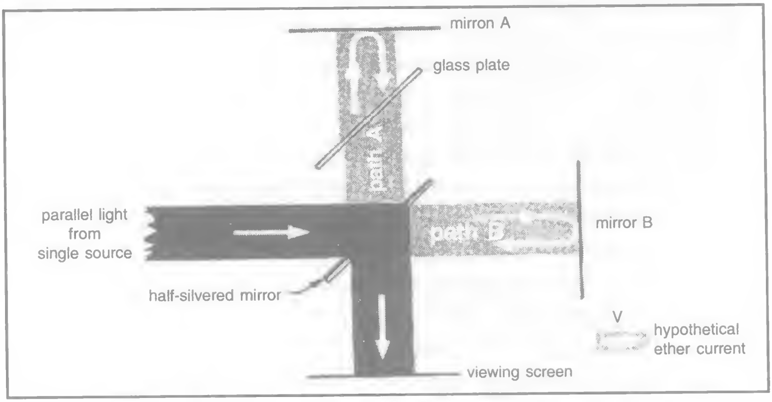


Fig 2 : The Michelson-Morley experiment

we can use the pair of light beams formed by a half silvered mirror (Figure 2). One of these light beams is directed to a mirror along a path perpendicular to the ether current, while the other goes to a mirror along a path parallel to the ether current. The optical arrangement is such that both beams return to the same viewing screen. The purpose of the clear glass plate is to ensure that both beams pass through the same thickness of air and glass.

If the path lengths of the two beams are exactly the same, they will arrive at the screen in phase and will interfere constructively to yield a bright field of view. The presence of an ether current in the direction shown, however, would cause the beams to have different transit times in going from the half silvered mirror to the screen, so that they would no longer arrive at the screen in phase but would interfere destructively. In essence this is the famous experiment performed in 1887 by Michelson and Morley.

In the actual experiment the two mirrors are not perfectly perpendicular, with the result that the viewing screen appears crossed with a series of bright and dark interference fringes due to differences in path length between adjacent light waves (Figure 3). If either of the optical paths in the apparatus is varied in length, the fringes appear to move across the screen as reinforcement and cancellation of the waves succeed one another at each point. The stationary

Fig 3 : Fringe Pattern observed in Michelson-Morley experiment

apparatus, then, can tell us nothing about any time difference between the two paths. When the apparatus is rotated by 90°, however, the two paths change their orientation relative to the hypothetical ether stream, so that the beam formerly requiring the time t_A (along parth A) for the round trip now required t_B (along path B) and vice versa. If these times are different, the fringes will move across the screen during the rotation.

This information can be used to calculate the fringe shift expected on the basis of the ether theory. The expected fringe shift 'n' in each path when the apparatus is rotated by 90° is given by

$n = Dv^2 / \lambda\ c^2$

Here, D is the distance between half silvered mirror and each of the other mirrors (made about 10 metres using multiple reflections), v is the ether speed - which is the Earth's orbital speed $3x10^4$ (m/s), c is the speed of the light = $3x10^8$ m/sec, and λ is the wave length of light used, about 5000Å (1Å=10^{-10}m), one then obtains n=0.2 fringe.

Since both paths experience this fringe shift, the total shift should amount to 2n or 0.4 fringe. A shift of this magnitude is readily observable, and therefore, Michelson and Morley looked forward to establishing directly the existence of the ether. *To everybody's surprise, no fringe shift whatever was found.* When the experiment was performed at different seasons of the year and in different locations, and when experiments of other kinds were tried for the same purpose, the conclusions were always identical: no motion through the ether was detected.

The negative result of the Michelson-Morley experiment had two consequences. First, it rendered untenable the hypothesis of the ether by demonstrating that the ether has no measurable properties – a tragic end for what had once been a respected idea. Second, it suggested a new physical principle: the speed of light in free space is the same everywhere, regardless of any motion of source or observer. As a result, the Michelson-Morley experiment has become the most famous "failed" experiment in the history of science. **They had started out to study the ether, only to conclude that the ether did not exist.** But if this were true, how could light move in "waves" without a medium to carry it? What's more, the experiment indicated that the velocity of light is always constant.

It was a completely unexpected conclusion. But the experiment was meticulous and the results irrefutable. Lord Kelvin (1824-1907), said in a lecture in 1900 at the Royal Institution that Michelson and Morley's experiment had been "carried out with most searching care to secure a trustworthy result," casting "a nineteenth century cloud over the dynamic theory of light". The conclusion troubled physicists everywhere, though. Apparently, they were wrong about the existence of the ether – and if they were wrong, then light was a wave that somehow could travel without a medium to travel through. Further, the Michelson - Morley results seemed to call into question the kind of Newtonian relativity that had been around for a couple of centuries and by this time was well tested; the idea that the speed of an object can differ, depending upon the reference frame of the observer. Suppose two cars are travelling along on a road. One car is going 80 kms per hour, the other 75 kms per hour. To the driver of the slower car, the faster car would be gaining ground at a rate of 5 kms per hour. Why would light be any different?

But that's just what the Michelson and Morley experiment had shown; *Light does behave differently.* The velocity of light is always constant – no matter what. Astronauts travelling in their spaceship at a speed of 2,90,000 km/sec alongside a beam of light (which travels at 3,00,000 km/sec) would not perceive the light gaining on them by 10,000 km/sec. They would see light travelling at a constant 3,00,000 km/sec. The speed of light is a universal absolute! Mind boggling, indeed!

The Special Theory of Relativity:

Surprisingly, Einstein never received a Nobel Prize for the most important paper that he published in 1905, the one that dealt with a theory that came to be known as the special theory of relativity.

He also tossed out the idea of the ether, which Michelson and Morley had called into question. Maxwell needed it because he

thought light travelled in waves, and if that were so, he thought, it needed some medium in which to travel. But what if, as Max Planck's (1858-1947) quantum theory stated, light travels in discrete packets or quanta? Then it would act more like particles and wouldn't require any medium to travel in.

Arthur Holly Compton

Antony Hewish

By making these assumptions — that the velocity of light is a constant, that there is no ether, that light travels in quanta and that motion is relative — he was able to show why the Michelson - Morley experiment came out as it did, without calling the validity of Maxwell's electromagnetic equations into question. But, where does "relativity" enter?

We mentioned earlier the role of the ether as a universal frame of reference with respect to which light waves were supposed to propagate. Whenever we speak of "motion", of course, we really mean motion relative to a "frame of reference". The frame of reference may be a road, the earth's surface, the sun, the center of our galaxy; but in every case we must specify it. Stones dropped in New Delhi and in Washington both fall "down", and yet the two move in opposite directions relative to the earth's center. Which is the correct location of the frame of reference in this situation, the earth's surface or its centre? The answer is that *all* frames of reference are equally correct, although one may be more convenient to use in a specific case. If there were an ether pervading all space, we could refer all motion to it, and the inhabitants of New Delhi and Washington would escape from their quandary. The absence of an ether, then, implies that there is no universal frame of reference, so that all motion exists solely relative to the person or instrument observing it.

The theory of relativity resulted from an analysis of the physical consequences implied by the absence of a universal frame of reference. The special theory of relativity treats problems involving the motion of frames of reference at constant velocity (that is, both constant speed and constant direction) with respect to one another; the general theory of relativity, proposed by Einstein a decade later, treats problems involving frames of reference accelerated with respect to one another. The special theory has had a profound influence on all of physics.

Carlo Rubbia

Enrico Fermi

The paper in which the young Albert Einstein in 1905 set out the special theory of relativity confronted common sense with several new and disquieting ideas. It abolished the ether, and it showed that matter and energy are equivalent. The new ideas derive from the central conception of relativity: that time does not run at the same pace for every observer. This bold conception lies at the heart of modern physics, all the way from the atomic to the cosmic scale. Yet it is still hard to grasp, and the paradoxes it pose continue to puzzle and to stimulate each generation of physicists.

Two Axioms

The special theory of relativity is based upon two axioms. The first states that **the laws of physics may be expressed in equations having the same form in all frames of reference moving at constant velocity with respect to one another.** This axiom expresses the absence of a universal frame of reference. If the laws of physics had different forms for different observers in relative motion, it could be determined from these differences which objects are "stationary" in space and which are "moving". But because there is no universal frame of reference, this distinction does not

Murray Gell-Mann

Joseph H.Taylor Jr

exist in nature; hence the above axiom. Consequently, this axiom implies that two observers, each of whom appears to the other to be moving with a constant speed in a straightline, cannot tell which of them is moving.

The second axiom of special relativity states that **the speed of light in free space has the same value for all observers, regardless of their state of motion.** This axiom follows directly from the result of the Michelson - Morley experiment, and implies that when both observers measure the speed of light, they will get the *same* answer.

Neither of these axioms was new in itself. The first axiom had long been implicit in the accepted laws of mechanics. The second one was beginning to be accepted as the natural interpretation of Michelson and Morley's experiment in 1887. What was new, then, in Einstein's analysis was not one axiom or the other but the confrontation of the two. **They form the two principles of relativity not singly but together.** This is how Einstein presented them jointly at the beginning of his paper.

So basically, in the special theory of relativity Einstein revamped Newtonian physics such that when he worked out the formulas, the relative speed of light always stayed the same. It never changes relative to anything else, even though other things change relative to each other. **Mass, space and time all vary depending upon how fast you move**. As observed by others, the faster you move, the greater your mass, the less space you take up and the more slowly time passes for you! **The more closely you approach the speed of light, the more pronounced these effects become.** Let us have a look at some of the consequences of the theory of relativity.

Time Dilation

It follows at once from the two axioms combined that we have to revise the traditional idea of time. By tradition we take it for granted that time is the same everywhere and for everyone. Why not? It seems natural to assume that time is a universal "now" for every traveller anywhere in the universe. But, according to the theory of special relativity, time cannot run at the same pace for two observers, one of whom is moving relative to the other, if they are to get the same speed (that is for light) when they time a beam of light that is moving with one of them. Consider this example.

Russel A. Hulse

Paul Adrien Maurice Dirac

If you were an astronaut travelling at 90 percent of the speed of light (about 2,70,000 kms per second), you could travel for five years (according to your calendar watch) and you'd return to Earth to find that 10 years had passed for the friends you'd left behind. Or, if you could accelerate your engines to help you travel at 99.99 percent of the speed of light, after traveling for only 6 months you'd find that 50 years had sped by our Earth during your absence!

Clocks moving with respect to an observer appear to tick less rapidly than they do when at rest with respect to him. If we, in the S frame, or the stationary frame of reference, observe the length of time *t* some event requires in a frame of reference *S'* in motion relative to us, our clock will indicate a longer time interval than the t_0 determined by a clock in the moving frame. This effect is called *time dilation.* According to the theory of relativity, *t* and t_o are related as $t = t_0 / \sqrt{1-v^2/c^2}$ where v is the speed of the frame of reference S' (the moving frame) with respect to S (the stationary frame in which the observer is situated). Obviously t is greater than t_0 as v cannot be greater than c. Thus, a stationary clock measures a longer time interval between events occurring in a moving frame of reference than does a clock in the moving frame.

So the laws of relativity say that time is relative; it does not always flow at the same rate for the two travellers moving relative to each other. For example, moving clocks slow down. In the 1960s a group of scientists at the University of Michigan took two sets of atomic clocks with an accuracy to 13 decimal places. They put one set of airplanes flying around the world. The other identical set remained behind on the ground. When the airplanes with the clocks landed, and those clocks were compared to the clocks that stayed still, the clocks that had ridden on the airplanes had actually ticked fewer times than those that had stayed on the ground.

Simon van der Meer

Sir Martin Ryle

It may also be remarked that when v approaches c, the processes in the moving frame S' appear to further slow down to an observer in S. When v=c, t becomes infinitely long! This equation then sets a speed limit on the moving frame S' which is equal to the speed of light.

Let us now consider a common objection raised against the theory of relativity. Since there is no absolute motion of any sort, there is no "preferred" frame of reference. It is always possible to choose a moving object as a fixed frame of reference without violating any natural law. Consider two brohters-twins, one of them being an astronant. When the earth is chosen as a frame, the astronaut makes the long journey, returns, finds himself younger than his stay-at-home brother. All well and good. But what happens when the spaceship is taken as the frame of reference (S)? Now, it must be assumed that the earth makes a long journey away from the ship and back again. In this case, it is the twin on the ship who is the stay-at-home. When the earth gets back to the spaceship, will not the earth rider be the younger? If so, the situation is more than a paradoxical affront to common sense. It is a logical contradiction. Clearly each twin cannot be younger than the other! A paradox! Not

Subrahmanyan Chandrasekhar

Stephen W.Hawking

really. The application of the theory of relativity shows that the twin that travelled indeed remains young than his twin stay-at-home brother! (See Box).

Length Contraction

Relativity also says that the faster an object moves, the more its size shrinks in the direction of its motion, as seen by a stationary observer. This implies that the length of an object in motion with respect to a stationary observer appears to be shorter than when it is at rest with respect to him, a phenomenon known as the *Lorentz - FitzGerald contraction.*

Because the relative velocity of the two frames S and S' the one moving with velocity v with respect to the frame S, appears only as v^2 in the equations, it does not matter which frame we call S and which S'. If we find that the length of a rocket is L_0 when it is on its launching pad, we willl find from the ground that its length L when moving with the speed v is $L = L_0 \sqrt{1-v^2/c^2}$, while to a man in the rocket, objects on the earth behind him appear shorter than they did when he was on the ground by the same factor $\sqrt{1-v^2/c^2}$. The length of an object is a maximum when measured in a reference frame in which it is moving. The relativistic length contraction is negligible for ordinary speeds, but, it is an important effect at speeds close to the speed of light. At a speed v=1500 km/sec or about 0.005 percent of the speed of light, L measured in the moving frame S' would be about 99.9985% of L_0, but when v is about 90% of the speed of light L would be only about 44% of L_0! It is worth emphasising the fact that the contraction in length occurs only in the direction of the relative motion.

A Striking Illustration

A striking illustration of both time dilation and the length contraction

The Twin Paradox

"Indeed, all sorts of objections were raised against relativity. One of the earliest, most persistent objections centred around a paradox that had been mentioned by Einstein in his 1905 paper himself. The workd "paradox" is used in the sense of something opposed to common sense, not something logically contradictory. It is usually described as a thought experiment involving twins. They synchronize their watches. One twin gets into a spaceship and makes a long trip through the space. When he returns, the twins compare their watches. According to the special theory of relativity, the traveller's watch will show a slightly earlier time. In other words, time on the spaceship would have gone at a slower rate than time on the earth!It may seem at first sight that the two observers who part and then meet again must necessarily be in a symmetrical relation. Whatever journey each has made is, after all, relative; and it may therefore seem as if each observer is free to say that he has not travelled at all and that all the travelling has been done by the other. Indeed, we may ask, does not the first axiom of relativity say this? Does not the first axiom say that two observers cannot tell which of them has moved and which of them has stayed still?No, it does not. What the first axiom of relativity says is something much sharper, something much more restricted and more precise. The first axiom says that if each of two observers seems to the other to be moving at a constant speed in a straight line, they cannot tell which of them is moving. But the axiom says nothing about observers in arbitrary motion. It says nothing about them if they do not move in straight lines and nothing about them if they do not move at a constant speed.Here is the crux of the matter. Two observers who separate and meet again cannot fulfill the conditions of the first axiom of relativity throughout such a journey. Suppose one of them remains still. Then the other can travel in a straight line going and coming, but if he does this, he must turn back at some point-that is, he must change his speed. Or the traveller can move at a constant speed, but if he does this, he cannot move in a straight line-he must move in a curve if he is to come back to his starting point. Two observers who part and meet again can fulfill one condition of the first axiom of relativity, if they wish, but they cannot fulfill both.And at once, as soon as a traveller departs from the conditions of the first axiom, he knows that he is moving. He feels the outside forces that produce a change of motion. If he is traveling in a straight line and has to come to rest, he knows physically that he is decelerating; he can tell that he is, by carrying an accelerometer and looking at it. Indeed, all he needs to carry is a bucket of water: if the surface begins to tilt, he knows that he is changing speed. In the same way, if the traveler is rounding a curve, he can tell that he is moving by the acceleration he feels-or by carrying an accelerometer or a bucket of water. We cannot detect a constant speed in a straight line: that is the first axiom of relativity. But we can detect any accelerated motion: that is a physical fact we have all experienced. Lying in a sleeping

compartment in the dark at night, we may not be able to tell whether the train is moving or not. But we can tell when the train brakes, and we can tell when it rounds a bend. We can tell because we are thrown about; we act as our own accelerometer.Therefore if I stay at home and you go on a journey and come back, the relation between us is not symmetrical. You can tell that you have traveled, even if you travel in a dark train-you can tell by carrying an accelerometer. And I can tell that I have stayed at home, because my accelerometer has recorded no change of speed or of direction. The traveller who makes a round trip can be distinguished from the stay-at-home.Now consider what happens to your clock, the traveller's. Imagine your round trip broken down into a series of short, straight paths, along each of which you can keep your speed constant. Then along each short path your clock seems to me to run slower than mine. When you return, your clock should be behind mine, by the sum of these losses; and you should have aged less than I. Can this be so? It can, and it. The difference in our timekeeping does not contradict any symmetry you may find in the situation. It does not contradict your finding that, along any short path, my clock also seems to you to be running slower than yours. Your findings do not add up because you do not remain faithful to the first axiom of relativity: your view of my time changes every time you move abruptly from one straight path to another. Only my view of your time losses accumulates steadily, because only I remain faithful to the first axiom of relativity throughout.

Source : J. Bronowski in "The Clock Paradox"
Scientific Amertican (January 1963)

occurs in the decay of unstable particles called m mesons. m mesons are created high in the atmosphere (several kilometres above the surface of the Earth) by fast cosmic ray particles arriving at the Earth from space and reach sea level in profusion travelling at 0.998 of the velocity of light. m mesons ordinarily would decay into electrons only in 2×10^{-6} seconds. During this time they may travel a distance of only 600 metres. However, relative to mesons, the distance (through which they travel) gets shortened while relative to us, their life span gets increased. Hence, despite their brief life-spans, it is possible for mesons to reach the ground from the considerable altitudes at which they are formed.

Heavier the Faster

One more interesting consequence of the special theory of relativity is that as the objects approach the speed of light, their mass approaches infinity. The mass m of a body measured while in motion in terms of m_0 when measured at rest are related by,

$m = m_0 \sqrt{1-v^2/c^2}$

The mass of a body moving at the speed of v relative to an observer is larger than its mass when at rest relative to the observer by the factor $1/\sqrt{1-v^2/c^2}$.

Relativistic mass increases are significant only at speeds approaching that of light. At a speed one tenth that of light the mass increase amounts to only 0.5 per cent, but this increase is over 100 per cent at a speed nine tenths that of light. Only atomic particles such as electrons, protons, mesons, and so on can have sufficiently high speeds for relativistic effects to be measurable, and in dealing with these particles the "ordinary" laws of physics cannot be used. Historically, the first confirmation of this effect was discovery by Bucherer in 1908 that the ratio e/m of the electron's charge to its mass is smaller for fast electrons than for slow ones; this equation, like the others of special relativity, has been verified by so many experiments that it is now recognized as one of the basic formulae of physics.

Mass? Energy? Or Mass Energy?

Here is yet another astounding consequnce of the theory of relativity. Using his famous equation, $E=mc^2$, Einstein showed that energy and mass are just two facets of the same thing. In this equation, E is energy, m is mass and c^2 is the square of the speed of light, which is a constant. So the amount of energy E, is equal to the mass of an object multiplied by the square of the speed of light.

In addition to its kinetic, potential, electromagnetic, thermal, and other familiar guises, then, energy can manifest itself as mass.

The conversion factor between the unit of mass (kg) and the unit of energy (joule) is c^2, so 1 kg of matter has an energy content of 9×10^{16} joules. Even a minute bit of matter represents a vast amount of energy.

Since mass and energy are not independent entities, the separate conservation principles of energy and mass are properly a single one, the principle of conservation of "mass energy". Mass can be created or destroyed, but only if an equivalent amount of energy simultaneously vanishes or comes into being, and vice versa.

It is this famous mass energy conversion relationship that is responsible for generation of energy in stars, atomic bombs, and the nuclear reactors!

Where common sense fails

The consequences of relativity described in the preceding paragraphs seems completely against all common sense. But common sense is based on everyday experience, and things don't get really strange with relativity until you venture into the very, very fast. Let us understand this aspect in some detail. Consider a rifleman in a jeep moving with velocity v with respect to the ground. The rifleman shoots a bullet in the forward direction with the muzzle velocity V. Now, the velocity of the bullet with respect to the ground, in accordance with the theory of relativity, will be, not V+v, but $(V + v) / (1 + vV/c^2)$, where c is the velocity of light. If both velocities V and v are small compared to the velocity of light, the second term in the denominator is practically zero and the old "common sense" formula holds. But either V or v, or both approach the velocity of light, the situation will be quite different. Consider $V = v = 0.75$ c. According to the common sense, the velocity of the bullet with respect to the ground should be 1.5 c, i.e. 50 per cent more than the velocity of light. However, putting $V = 0.75$ c and $v = 0.75$ c in the above formula, we get 0.96 c for the velocity of bullet with respect to the ground, which is still less than the speed of light! In the limiting case, if we make V, and the velocity of the jeep $v = c$, we obtain, $(c + c) / (1 + (c^2) / c^2) = c$

Fantastic as it may look at first sight, Einstein's law for the addition of two velocities is correct and has been confirmed by direct experiments. Thus Einstein's theory of relativity leads us to the conclusion that it is impossible to exceed the velocity of light by adding two (or more) velocities no matter how close each of these velocities is to that of light! *The velocity of light, therefore, assumes the role of a universal speed limit*, which cannot be exceeded no matter what we do! No matter how strenge the idea of relativity may seem, we may remember that every experimental test of this theory till date has confirmed that Einstein was right!

The Four Dimensions

"According to Einstein's views, space and time are more intimately connected with one another than it was supposed before and within certain limits, the notion of space may be substituted by the notion of time and vice versa. To make this statement more clear, let us consider a passenger in a train having his meal in the dining car. The waiter serving him will know that the passenger ate his soup, meals and dessert in the same place, that is, at the same table in the dining car. But, from the point of view of a person on the ground, the same passenger consumed the three courses at points along the track separated by many kilometres. We can hence make the following trivial statement: ***Events taking place in the same place but at different times in a moving system will be considered by a ground observer as taking place at different places.*** *Now, following Einstein's idea concerning the reciprocity of space and time, let us replace in the above statement the word "place" by the word "time" and vice versa. The statement will now read:* ***Events taking place at the same time but in different places in a moving system will be considered by a ground observer as taking place at different times.*** *This statement is far from being trivial. It means that if, for example, two passengers at the far ends of the dining car had their after-dinner coffee sipped simultaneously from the point of view of the dining-car waiter, the person standing on the ground will insist that the coffee was sipped at different times! Since according to the principle of relativity, neither of the two reference systems should be preferred to the other (the train moves relative to the ground or the ground moves relative to the train), we do not have any reason to take the waiter's impression as being true and ground observer's impression as being wrong or vice versa. Of course, this would not be apparent to you if you were the ground observer. This is so because the distance of, say, 30 metres between two passengers sipping their after dinner coffee at opposite ends of the dining car translates into a time interval of only 10^{-8} seconds, and there is no wonder that this is not apparent to our senses. It would become appreciable when the train travels close to the speed of light. The transformation of time intervals into space intervals and vice versa was given a simple geometrical interpretation by the German mathematician H. Minkowski. He proposed that time or duration be considered as the fourth dimension supplementing the three spatial dimensions (x, y, z) and that transformation from one system of reference to another be considered as a rotation of co-ordinates systems in this four dimensional space. A point in these four dimensional space is called an event. Relativistic effects like the length contraction and the time dilation then become consequences of the rotation of these space-time co-ordinates. These effects being relative, each of the two observers moving with respect to one another will see the other fellow as somewhat flattened in the direction of his motion and will consider his watch to be slow!"*

- George Gamow and John M. Cleveland in Physics : Foundation and Frontiers Prentice Hall of India (1966)

The General Theory of Relativity

How does the general theory of relativity differ from the special theory? Let us have a brief look.

Strangely enough, it was another four years after Einstein's publication of his papers on the photoelectric effect, Brownian motion and the special theory of relativity, before he succeeded in securing a teaching position at the University of Zurich — and a poorly paying one at that. But by 1913, thanks to the influence of Planck, the Kaiser Wilhelm Institute near Berlin created a position for him. Ever since his 1905 publications, Einstein had been working on a bigger theory: his general theory of relativity. The special theory had applied only to steady movement in a straight line. But what happened when a moving object sped up or slowed down or curved in a spiral path? In 1916, he published his general theory of relativity, which had vast implications, especially on the cosmological scale. **Many physicists consider it the most elegant intellectual achievement of all time.**

The general theory preserves the tenets of the special theory while adding a new way of looking at gravity — because gravity is the force that causes acceleration and deceleration and curves the paths of moons around planets, of planets around the sun, and so on. Einstein realized that there is no way to tell the difference between the effects of gravity and the effects of acceleration. So he abandoned the idea of gravity as a force and talked about it instead as an artifact of the way we observe objects moving through space and time. According to Einstein's relativity, a fourth dimension — time — joins the three dimensions of space (height, length and width), and the four dimensions together form what is known as the space time continuum.

To illustrate the idea that acceleration and gravity produce essentially the same effects, Einstein used the example of an elevator, with its cables broken, falling from the top floor of a building. As the elevator falls, the effect on the occupants is "weightlessness", as if they were aboard a spaceship. For that moment they are in free fall around the Earth. If the people inside couldn't see anything outside the elevator, they would have no way to tell the difference between this experience and the experience of flying aboard a spaceship in orbit.

Einstein made use of this equivalence to write equations that saw gravity not as a force, but as a curvature in space time — much as if each great body were located on the surface of a great rubber sheet (Figure 4). A large object, such as a star, bends or warps space time, much like a large ball resting on a rubber sheet

General Relativity and Black Holes

The Universe is expanding, exactly as the pure equations of general relativity predicted in 1917. Then, Einstein himself refused to believe the evidence of his own theory! Indeed, Einstein's equations provide the basis for the highly successful Big Bang description of the birth and evolution of the entire Universe. Within the expanding Universe, general relativity is required to explain the workings of exotic objects where space-time is highly distorted by the presence of matter where large masses produce strong gravitational fields. The most extreme version of this, and one that has caught the popular imagination, is the phenomenon of black holes. Black holes would trap light by their gravitational pull – or, in terms of general relativity, by bending space-time around themselves so much that it becomes closed, pinched off from the rest of the Universe. If a star keeps the same mass but shrinks inwards, or stays the same size while accumulating mass, density increases. Eventually, the distortion of space-time around it increases until, a situation is reached where the object collapses aand folds space-time around itself, disappearing from all outside view. Not even light can escape from its gravitational grip, and it has become a black hole. The notion of such stellar mass black holes seemed no more than a mathematical trick – something that surely could not be allowed to exist in the real Universe, until 1968, and the discovery of pulsars which are rapidly spinning neutron stars. A good deal of our understanding about black holes is due to the work of the legendary physicist of today, Stephen Hawking.

would cause a depression or sagging on its surface. The distortions caused by masses in the shape of space and time result in what we call gravity. What people call the "force" of gravity is not really a characteristic of objects like stars or planets, but comes from the shape of space itself.

In fact, this curvature has been confirmed experimentally. Einstein made predictions in three areas in which his general theory was in conflict with Newton's theory of gravity:

1. Einstein's general theory allowed for a shift in a perihelion (the point nearest the Sun) of a planet's orbit as shown in Figure 5. Such a shift in Mercury's orbit had baffled astronomers for years to which the general theory of relativity offered an explanation.
2. Light in an intense gravitational field should show a red shift as it fights against gravity to leave a star. Indeed, comparing the vibration frequencies of spectral lines in sunlight with light emitted

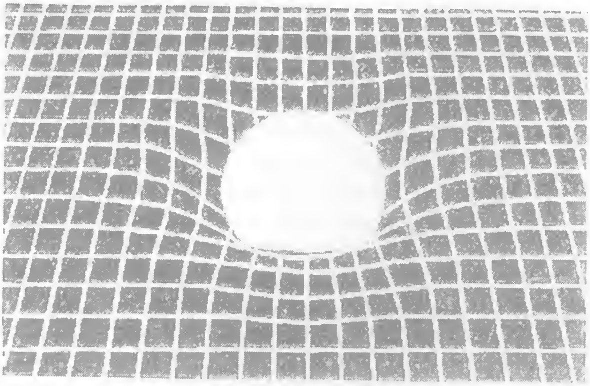


Fig 4 : A heavy object placed on a streched rubber sheet makes an indentation.The Presence of the Sun "indents" space time in an analogous manner

by terrestrial sources, astronomers have found that in the former case all vibration periods are lengthened (or frequencies reduced implying the "red shift") by about 2 x 10^{-4} per cent, which is exactly the value predicted by Einstein's theory. Consequenlty, the spectrum observed appears to shift towards the red and as observed on the Earth, exhibiting the gravitational red shift.

3. Light should be deflected by a gravitational field much more than Newton predicted (Figure 6). On March 29, 1919, a total

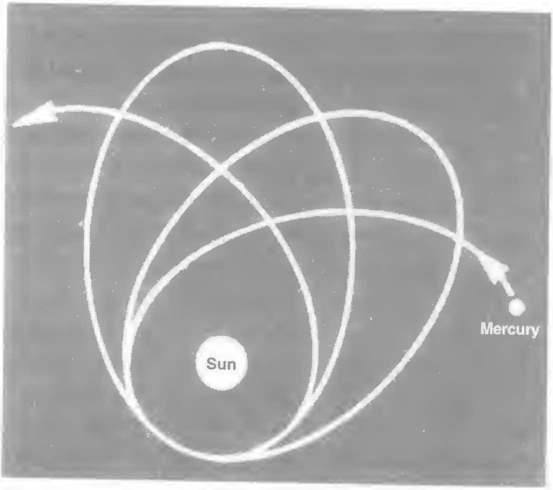


Fig 5 : The curious shape of the orbit of Mercury is explained by general relativity

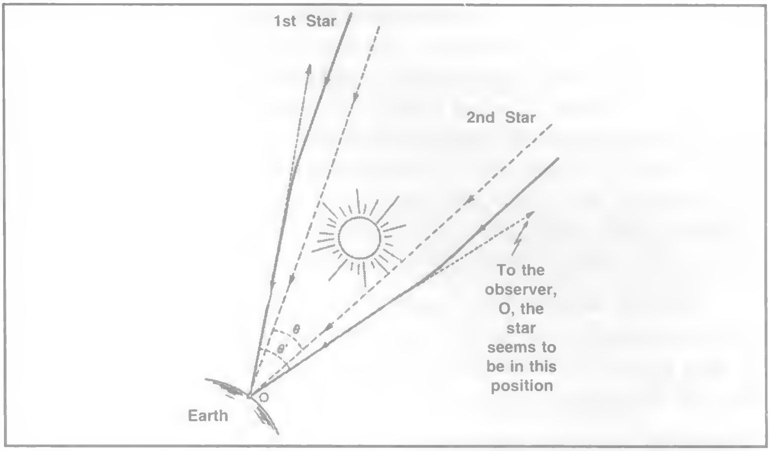


Fig 6 : The deviation of light from a star when the light passes closed to the sun

solar eclipse occurred over Brazil and the coast of West Africa. In the darkened day-time sky, the measurements of the nearby stars were taken. Then they were compared with those taken in the midnight sky six months earlier when the same stars had been nowhere near the Sun. The predicted deflection of the star-light was observed and Einstein was proved right. He rapidly became the most famous scientist in the world, and his name became a household word.

Always a Catalyst

Germany–one of the premier cradles of great work in all the sciences–rapidly became less and less hospitable to the large group of outstanding scientists who worked there, especially the many who, like Einstein, were counted among the Nazis' Jewish targets. By the 1930s an exodus had begun, including many non-Jewish scientists who left on principle, no longer willing to work where their colleagues were persecuted. In 1930, Einstein left Germany for good. He came to the United States to lecture at the California Institute of Technology, and never went back to Germany afterward. He accepted a position at the Institute of Advanced Study in Princeton, New Jersey, where he became a permanent presence, and in 1940 he became an American citizen.

Always a catalyst among his colleagues for thoughtful reflection, Einstein remained active throughout his life in the world of Physics. But even this renegade found, as Planck did, that Physics was changing faster than he was willing to accept. On the horizon loomed

challenges to reason that he was never able to accept – such as Niels Bohr's complementarity and Werner Heisenberg's uncertainty principle. "God does not play dice with the universe," Einstein would grumble, or "God may be subtle, but He is not malicious." During the last decades of his life Einstein spent much of his time searching for a way to embrace both gravitation and electromagnetic phenomena. He never succeeded, but continued to be, to his final days, a solitary quester, putting forward his questions to nature and humanity, seeking always the ultimate beauty of truth.

Einstein received the Nobel Prize in Physics for the year 1921, not for relativity, but for the interpretation of the photoelectric effect. It was given "for his services to theoretical physics, and especially for his discovery of the law of the photoelectric effect".

Relativity – Any challenge?

True, there have been a few challenges to the theory of relativity once in a while – both theoretical and experimental. Nearly three decades ago, our own E.C.G. Sudarshan had predicted the possibility of "Tachyons" – the particles that travelled at a speed greater than light, but, in a different realm. They could not travel at a speed lower than the speed of light. It may be noted that such particles cannot carry any information.

There have even been challenges to the constancy of the speed of light in vacuum. Recently, there has been a measurement by a team of Italian physicists that appears to indicate that they can send a faster-than-light pulse of microwaves over more than a metre. In Einstein's theory, time races forwards as if on a light beam. If an object were to travel faster than c, it would move backwards in time, violating the principle of causality which says that cause must always precede the effect. The alternative seems nonsensical as illustrated by the following limerick:

There was a young lady named Bright
whose speed was far faster than light
She went out one day
In a relative way
And returned the previous night.

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Nobel Prizes awarded for work on Relativity and/or its applications.

1902	Hendrik Antoon Lorentz	The Netherlands	in recognition of his extraordinary service he rendered by his researches into the influence of magnetism upon radiation phenomena
1907	Albert Abraham Michelson	USA	for his optical precision instruments and the spectroscopic and metrological investigations carried out with their aid
1927	Arthur Holly Compton	USA	for his discovery of the effect named after him
1933	Paul Adrien Maurice Dirac	Great Britain	for the discovery of new productive forms of atomic theory
1938	Enrico Fermi	Italy	for his demonstrations of the existence of new radioactive elements produced by neutron irradiation, and for his related discovery of nuclear reactions brought about by slow neutrons
1969	Murray Gell-Mann	USA	for his contributions and discoveries concerning the classification of elementary particles and their interactions

1974	Sir Martin Ryle	Great Britain	for his pioneering research in radio astrophysics: for his observations and inventions, in particular of the aperture synthesis technique
	Antony Hewish	Great Britain	for his decisive role in the discovery of pulsars
1983	Subrhamanyan Chandrasekhar	USA	for his theoretical studies of the physical processes of importance to the structure and evolution of the stars
1984	Carlo Rubbia	Italy	for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction
	Simon van der Meer	the Netherlands	-do-
1993	Russell A. Hulse	USA	in discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation
	Joseph H. Taylor Jr	USA	-do-

Note: It is interesting to note that Albert Einstein – the father of relativity – did not receive Nobel Prize for propounding the theory of relativity. He was awarded Nobel Prize in Physics for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect

Glossary

Important terms used in connection with Relativity are given below. The terms given do not necessarily appear in the present article.

Absolute Zero : The temperature of -273.16° c or -459.69° F or ok thought to be the temperature at which molecular motion vanishes and a body would have no heat energ.

Aphelion : The point of a planetary orbit farthest from the Sun.

Black hole : Black hole is a collapsed object, such as a star, that has become invisible. It is formed when a massive star runs out of thermonuclear fuel and is crushed by its own gravitational force. It has such a strong gravitational force that nothing can escape from its surface, not even light. Though invisible, it can capture matter and light from the outside.

Cosmology : The study of the overall structure of the physicala universe.

Curvature of space: The deviation of a spacelike three-dimensional subspace of curved space-time from euclidean geometry.

Curved space-time: A four-dimensional space, in which there are no straight lines but only curves, which is a generalization of the Minkowski universe in the general theory of relativity.

Equivalence principle : In general relativity, the principle that the observable local effects of a gravitational field are indistinguishable from those arising from acceleration of the frame of reference. Also known as Einstein's equivalence principle; principle of equivalence.

Event : A point in space-time.

FitzGerald-Lorentz contraction: The contraction of a moving body in the direction of its motion when it speed is comparable to the speed of light. Also known as Lorentz contraction: Lorentz-FitzGerald contraction.

Four-vector : A set of four quantities which transform under a Lorentz transformation in the same way as the three space coordinates and the time coordinate of an event. Also known as Lorentz four-vector.

Four-velocity : A four-vector whose components are the rates of change of the space and time coordinates of a particle with respect to the particle's proper time.

Frame of reference : A coordinate system for the purpose of assigning positions and times to events. Also known as refrence frame.

Geodesic : A curve joining two points in a Riemannian manifold which has minimum length.

Geodesic motion : Motion of a particle along a geodesic path in the four dimensional space-time continuum; according to general relativitiy, this is the motion which occurs in the absence of nongravitational forces.

Gravitation : The mutual attraction between all masses in the universe. Also known as gravitational attraction.

Gravitational collapse : The implosion of a star or other astronomical body from an initial size to a size hundreds or thousands of times smaller.

Gravitational constant : The constant of proportionality in Newton's law of gravitation, equal to the gravitational force between any two particles times the square of the distance between them, divided by the product of their masses.

Gravitational field: The field in a region in space in which a test particle would experience a gravitational force; quantitatively, the gravitational force per unit mass on the particle at a particular point.

Gravity : The gravitational attraction at the surface of a planet or other celestial body.

Lorentz frame : Any of the family of inertial coordinate systems, with three space coordinates and one time coordinate, used in the special theory of relativity; each frame is in uniform motion with respect to all the other Lorentz frames, and the interval between any two events is the same in all frames.

Lorentz invariance: The property, possessed by the laws of physics and of certain physical quantities, of being the same in any Lorentz frame, and thus unchanged by a Lorentz transformation.

Lorentz transformation: Any of the family of mathematical transformations used in the special theory of relativity to relate the space and time variables of different Lorentz frames.

Mass-energy conservation: The principle that energy cannot be created or destroyed; however, one form of energy is that which a particle has because of its rest mass, equal to this mass times the square of the speed of light.

Mass-energy relation: The relation whereby the total energy content of a body is equal to its inertial mass times the square of the speed of light.

Minkowski universe: Space time as described by the four coordinates (x, y, z, ict), where i is the imaginary unit of c is the speed of light; Lorentz transformations of space-time are orthogonal transformations of the Minkowski world. Also known as Minkowski world.

Neutron star : A star that is supposed to occur in the final stage of stellar evolution; it consists of a superdense mass mainly of neutrons, and has a strong gravitational attraction from which only neutrinos and high-energy photons could escape so that the star is invisible.

Perihelion : The point of a planetary orbit closet to the Sun.

Principle of covariance : In classical physics and in special relativity, the principle that the laws of physics take the same mathematical form in all inertial reference frames.

Pulsar: Variable star whose luminosity fluctuates as the star expands and contracts; the variation in brightness is thought to come from the periodic change of radiant energy to gravitational energy and back. Also known as pulsating star.

Quasar : Quasi-stellar astronomical object, often a radio source; all quasars have large red shifts; they have small optical diameter, but may have large radio diameter. Also known as quasi-stellar object (QSO).

Relative : Related to a moving point; apparent, as relative wind, relative movement.

Relative momentum: The momentum of a body in a reference frame in which another specified body is fixed.

Relative motion : The continuous change of position of a body with respect to a second body, that is, in a reference frame where the second body is fixed.

Relativistic kinematics: A description of the motion of particles compatible with the special theory of relativity, without reference to the causes of motion.

Relativistic mass : The mass of a particle moving at a velocity exceeding about one-tenth the velocity of light; it is significantly larger than the rest mass.

Relativistic mechanics : Any form of mechanics compatible with either the special or the general theory of relativity.

Relativistic particle: A particle moving at a speed comparable with the speed of light.

Relativistic quantum theory: The quantum theory of particles which is consistent with the special theory of relativity, and thus can describe particles moving close to the speed of light.

Relativistic theory: Any theory which is consistent with the special or general theory of relativity.

Relativity : Theory of physics which recognizes the universal character of the propagation speed of light and the consequent dependence of space, time, and other mechanical measurements on the motion of the observer performing the measurements; it has two main divisions, the special theory and the general theory.

Slowing of clocks : According to the special theory of relativity, a clock appears to tick less rapidly to an observer moving relative to the clock than to an observer who is at rest with respect to the clock. Also known as time dilation effect.

Space coordinates: A three-dimensional system of cartesian coordinates by which a point is located by three magnitudes indicating distance from three planes which intersect at a point.

Spacelike surface: A three-dimensional surface in a four-dimensional space-time which has the property that no event on the surface lies in the past or the future of any other event on the surface.

Spacelike vector: A four vector in Minkowski space whose space component has a magnitude which is greater than the magnitude of its time component multiplied by the speed of light.

Space-time : A four-dimensional space used to represent the universe in the theory of relativity, with three dimensions corresponding to ordinary space and the fourth to time. Also known as space-time continuum.

Special relativity : The division of relativity theory which relates the observations of observers moving with constant relative velocities and postulates that natural laws are the same for all such observers.